Novel Control of a SSSC Connecting the United Arab Emirates and Oman on the GCC Power Grid Interconnection

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Abstract

The proposed work is novel design and controllability optimization technique which has been implemented prudently to simulate SSSC control operations in order to identify and determine various control parameters which are contributing considerably to control SSSC device operations in multiple directions in a power system network at different locations on the GCC power grid during any undesired conditions. In order to maximize utilization of SSSC control device operations on the GCC power grid, hereby SSSC control parameters are configured in different strategic ways to optimize SSSC model performance by adjusting its control parameters more tangibly under both steady and dynamic states. Herein SSSC device operational controllability results are clearly indicating that introduction of SSSC device in between the Oman and United Arab Emirates network will reasonably enhance the power system loadability, minimizing the losses and improved sustainability of the power system performance throughout the GCC power grid. Hereafter, new SSSC control device optimization technique can thus be successfully used for this type of optimization process.

Keywords

Controllability; Gain control; Wideband Delphi; Reactive Power

Introduction

The GCC region has become a hub of major economic growth in the world. It is providing financial support and incentives to the GCC countries. Hereby, it has witnessed population growth and large scale industrial activities in the GCC countries. This has led to increased demand for electricity. Based on various analyses, we determine that current demand for GCC power consumption is about 60 GW and it is projected that it will reach 180 GW within next 25 years. In order to maintain a reliable, sustainable, and well controlled power transfer between the GCC countries, it decided to interconnect the GCC countries. The interconnection is divided into two basic segmental links, neighbouring to neighbouring and common-link topologies. Firstly, Oman and United Arab Emirates are interconnected through neighbouring to neighbouring control topologies Secondly, Qatar, Bahrain, Saudi Arabia and Kuwait are interconnected through common-link control topology and this is also known as the Northern System. In the third stage common-link topology demonstrates UAE national grid and Oman northern grid interconnection; this is known as southern systems. Thirdly, southern and northern power systems are connected through hybrid link control topology. However, to improve these interconnected topologies, a large numbers of studies have been conducted to determine the technical and economic viability of the interconnection. The studies also demonstrate areas that require additional control devices. FACTS controllers are, therefore, strong candidates' technology options. Applications of FACTS Controllers will result into the following benefits [1],[3],[6].

- Increased Power Transfer capability
- Improved reliability
- Improved controllability
- Enhanced angle and voltage stability

FIG.1 illustrates the designed power exchange in between GCC countries and FIG.2 shows an inter-tie

connection in between the GCC countries. Prime contributions of this research work are as listed below.

- Investigate the SSSC impact in between the United Arab Emirates and Oman on GCC power grid with new PID control technique.
- Compare the system with and without SSSC

Successful implementation of SSSC will increase the network loadiability and enhanced system stability. The rest of this paper is organized as follows. In the first section research study introduction, GCC power system background, SSSC reinforcement plan and selection process are described. In the second and third sections SSSC control model case study, SSSC model's optimized dynamic response, effectiveness of SSSC, novel control of SSSC device operations are described. In the fourth, and fifth sections SSSC results discussion (selection process significance, controller significance and SSSC impact), conclusion are presented.

GCC Power System Background Information

The GCC power system facilities are configured and implemented into 8th strategic ways to meet reliable and sustainable industrial and domestic power system requirements at Gulf Corporative Council power network as shown in FIG.1. Firstly, a double-circuit 400 kV, 50 Hz line stretching from Al Zour (Kuwait) to Ghunan (Saudi Arabia) with an intermediate connection at Fadhili (Kingdom Saudi Arabia) and its associated power system facilities. Secondly, a back-to-back HVDC link introduced as a 380 kV interconnection, 60 Hz, system at Fadhili (KSA) in order to maintain proper synchronization or communication with other GCC power systems, which are operating at 50Hz frequency. Thirdly, a double circuit 400 kV overhead line stretching and partially connected with submarine link from Ghunan (KSA) to Al Jasra (Bahrain) along with its associated power system facilities. Fourthly, a double circuit 400 kV line stretching from Ghunan (KSA) to Salwa (Qatar) into Saudi Arabia along with its associated substations. Fifthly, a double circuit 400 kV line stretching from Salwa (Qatar) to Doha South and its associated facilities. Sixthly, a double circuit 400 kV, 50 Hz line stretching from Salwa (Qatar) to Ghuwaifat (United Arab Emirates) along with its associated power system facilities. Seventhly, a double and a single circuit 220 kV,50Hz line stretching from Al Ouhah (United Arab Emirates) to Al Wasset (Oman) along with its associated substations. Finally, a centralized control room was established at Ghunan (KSA) in order to control power system operations within all GCC countries with a certain degree of precision at different voltage and shared power perspective[2],[4].

System Reinforcement Plan

In order to initiate proper power system reinforcement plan, multiple studies at different voltage levels have been completed to determine power system operational requirements at both sides of United Emirates and Oman. This study reveals the Oman and United Arab Emirates substation sites are selected for the SSSC installation for the following reasons: firstly as demonstrated in GCC power system background that Oman and United Arab Emirates have an interconnection with industrial and domestic consumers at Al-Fuhah (United Arab Emirates) and Al-Wasset (Oman) power facilities. Based on power authorities investigation report which identified that there are couple of stability issues may exist on their systems, and consequently, also on the consumers' side of the system. This is very much viable to utilize the ability of the SSSC to improve all types of existing and potential stability issues in between Oman and United Arab Emirates power system facilities. The second strategic approach as demonstrated in FIG.1 that the main transmission line coming out from KSA, Kuwait, Qatar, Bahrain, United Arab Emirates 400kV bus is exposed to an increase in voltage levels during light load conditions due to the inherent shunt capacitance of the 400kV transmission line. Likewise, the 220kV bus is exposed to a reduction in voltage levels during peak load conditions on both sides of United Arab Emirates and Oman. The Al-Fuhah substation (UAE) and Al-Wasset Substation (Oman) sites are the best locations on the Oman and United Arab Emirates network where the total symmetrical range of the reactive output from the SSSC, from full inductive to full capacitive, could be utilized without applying fixed capacitors.

SSSC Model's Distributed Control

Appendix 1 introduced and demonstrated that the SSSC control model's three distributed control limits are defined as minimum, medium and maximum. These deviations are compensated at three operating limits by adjusting the SSSC control device with corresponding P & I control values as stated in appendix 1 FIG.5 and Table 8. The SSSC control device oscillates based on the corresponding P & I value of each limit in between at +/-2%, +/-4% and +/-6%

deviation at both sides of the transmission lines to adjust reactive power compensation as required. These control boundaries customized P &I values are enabling the control system to communicate each limit accurately and adjust the reactive power compensation based on sending and receiving ends voltage deviations in between Oman and UAE on the GCC power grid. These control boundaries will effectively operate when more than one FACTS device will be in operation at different locations on the GCC power grid. These will communicate to each other based on voltage, impedance, angle and power deviation at the sending and receiving ends of the Oman and United Arab Emirates power system facilities.

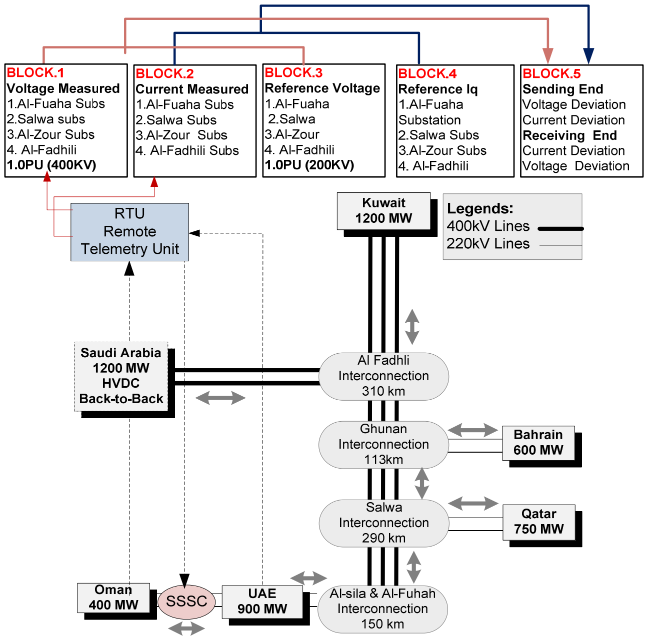

FIG.1 GCC COUNTRIES CURRENT POWER SHARING OPERATIONS

SSSC Controller's Selection Process

Based on comprehensive feedback received from the highly skilled personnel from industry and academia, a strong portal is developed. These inputs are integrated by using Wideband Delphi technique in order to investigate generate and allocate near optimal values of significant and submission criteria(s) as established in Table 1, 2 and 3. Equation (1) represents the mathematical method to determine CRVz value of each FACTS device derived from its significance and submission criteria(s). Equation (1) also indicates the functionality of the measurement model.

$$CRV_Z = \sum_{n=1}^{12} \frac{X_n}{100} xY \left(\frac{X_1}{100}.Y1 + \frac{X_2}{100} xY + \frac{X_3}{100}.Y2 \ldots. + \frac{X_{12}}{100}.Y3 \right) \quad \ldots\ldots\ldots\ldots (1)$$

Where:

CRVz (credible value)

z (subscript): SSSC, UPFC, IPFC, STATCOM etc

X_1 to X_{12} (Table 1 indicates the significant values of the FACTS devices)

Y (Submission criteria of each segment of design significant as shown in Table 2)

Tables 4 and 5 show the calculated score CRVz of each device based on the criteria as stated in Tables 1 & 2, using equation (1). If the summation score in Tables 4 and 5 of any device is above 65, it means good submission and 80 is significant (strong candidate). The Wideband Delphi technique is thus very effective in providing a basis for near optimization of important supporting [5],[10] parameters in order to formulate selection process of FACTS devices more pragmatically. Based on the above mentioned calculation score, the SSSC device attained a 71.75 weighted score and was selected to be implemented in between Oman and UAE . FIG.2 indicates the exact location of the SSSC to be implemented[15],[16].

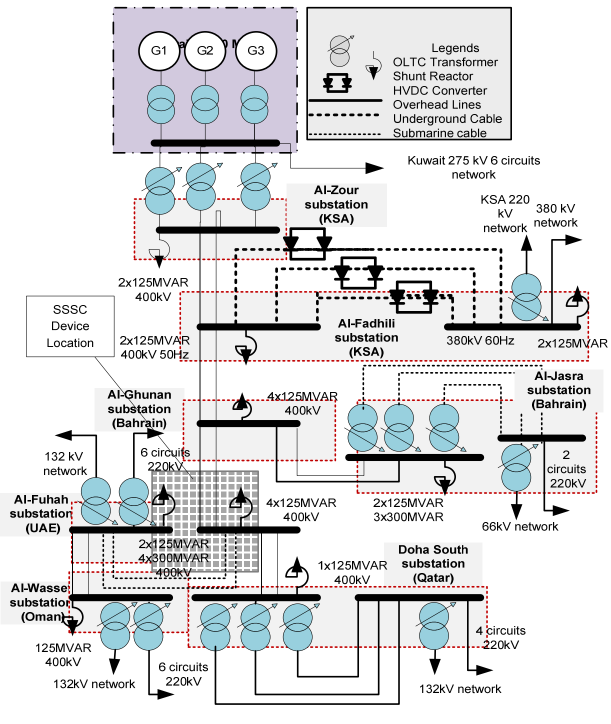

FIG.2. SINGLE LINE DIAGRAM OF GCC INTERCONNECTION AND SSSC DEVICE LOCATION

TABLE 1 FACTS DEVICES SELECTION CERITERIA

Criteria	$B_{1...12}$	$Y_{1...12}$	Equation (1)	Weighted Score
Control Significance	**15**	80	$(B_1/100).Y_1$	12.00
Control Integration	**10**	65	$(B_2/100).Y_2$	6.50
Design Capacity	**5**	65	$(B_3/100).Y_3$	3.25
Reliability	**10**	80	$(B_4/100).Y_4$	8.00
Maintenance frequency	**15**	80	$(B_5/100).Y_5$	12.00
Availability for trial	**5**	50	$(B_6/100).Y_6$	2.50
Refuse disposal	**5**	50	$(B_7/100).Y_7$	2.50
Monitoring equipment	**5**	50	$(B_8/100).Y_8$	2.50
Simulation results	**10**	80	$(B_9/100).Y_9$	8.00
Capex	**10**	80	$(B_{10}/100).Y_{10}$	8.00
Opex	**5**	65	$(B_{11}/100).Y_{11}$	3.25
Post Installation Support	**5**	65	$(B_{12}/100).Y_{12}$	3.25
Total	100	810	-	71.75

TABLE 2.FACTS DEVICES SELECTION CERITERIA SCOREBOARD

Criteria Description	Submission Score
No submission of any consequence	0
Some submission but unacceptably low	20
Satisfactory	50
Good submission	65
Significantly above the minimum acceptable. Considered a strong candidate.	80
Exceptional submission	100

TABLE 3.FACTS DEVICES ESTIMATED SCORE

Device	Submission Score	Device	Submission Score
TCVR	65.75	STATCOM	63.53
TCPAR	57.50	SVC	62.75
UPFC	66.50	GCSC	66.50
IPFC	62.00	TSSC	61.25
SSSC	71.75	TCSC	53.10

TABLE 4. FACTS DEVICES CALCULATED SCORE

Static Shunt Compensator			*Static Series Compensator*		
STATCOM		**SVC**	**GCSC**	**TSSC**	**SSSC**
S.No	**Weighted Score**	**Weighted Score**	**Weighted Score**	**Weighted Score**	**Weighted Score**
1	9.75	12.00	12.00	12.00	12.00
2	5.00	6.50	8.00	6.50	6.50
3	2.50	2.50	3.25	3.25	3.25
4	6.50	6.50	5.00	8.00	8.00
5	12.00	9.75	9.75	12.00	12.00
6	2.50	2.50	3.25	2.50	2.50
7	2.50	2.50	3.25	1.00	2.50
8	3.25	3.25	4.00	1.00	2.50
9	6.50	6.50	6.50	6.50	8.00
10	6.50	5.00	6.50	5.00	8.00
11	3.25	2.50	2.50	2.50	3.25
12	3.25	3.25	2.50	1.00	3.25
Total	63.50	62.75	66.50	61.25	71.75

TABLE 5. FACTS DEVICES CALCULATED SCORE

Static voltage and phase Angle control			*Combined Compensator*		*Static Series Compensator*
TCVR		**TCPAR**	**UPFC**	**IPFC**	**TCSC**
S.No	**Weighte d Score**	**Weighted Score**	**Weighted Score**	**Weighted Score**	**Weighted Score**
1	12.00	12.00	12.00	9.75	12.00
2	8.00	8.00	8.00	5.00	5.00
3	2.50	2.50	2.50	2.50	2.50
4	6.50	6.50	6.50	6.50	8.00
5	9.75	9.75	9.75	9.75	7.50
6	3.25	2.50	2.50	4.00	3.25
7	3.25	2.50	3.25	2.50	2.50
8	2.50	2.50	2.50	3.25	2.60
9	6.50	5.00	6.50	5.00	2.00
10	6.50	2.00	6.50	6.50	2.00
11	2.50	3.25	3.25	3.25	3.25
12	2.50	1.00	3.25	4.00	2.50
Total	65.75	57.50	66.50	62.00	53.10

SSSC Control Model Case Study

A 250-Mvar SSSC regulates voltage on a three-bus 220-kV long transmission system. During steady-state operation the SSSC control system keeps the fundamental component of the VSC voltage in phase with the system voltage. If the voltage generated by the VSC is higher (or lower) than the system voltage, the SSSC generates (or absorbs) reactive power. The amount of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance. The fundamental component of VSC voltage is controlled by varying the DC bus voltage. In order to vary the DC voltage, and therefore the reactive power, the VSC voltage angle (alpha) which is normally kept close to zero is temporarily phase shifted. This VSC voltage lag or lead produces a temporary flow of active power which results in an increase or decrease of capacitor voltages. FIG.1. illustrates 400 MW power exchanged in between Oman and United Arab Emirates into the shared GCC Power grid. As shown by the waveforms, the transmission line voltage and reactive current are well controlled by implementing the optimized control technique with a high degree of precision [8], [12],[13].

SSSC Optimized Dynamic Response

FIG.3 shows the operations of the SSSC its voltage control mode and its reference voltage is set to Vref=1.0 pu. The voltage droop of the regulator is 0.035 pu/100 VA. Therefore, when the SSSC operating point changes from fully capacitive (+250 Mvar) to fully inductive (-250 Mvar) as demonstrated into Fig.4.

1. The first waveform of SSSC shows voltage varies between 0.95 to 1.05 pu. The Voltage source is set at 1.040 pu, resulting in a 1.0 pu voltage at SVC terminals when the SSSC is out of service. In fact, when the reference voltage (Vref) is set to 1.0 pu, the SSSC is initially floating (zero current). The DC voltage is 15.3 kV. At t=0.5s and the voltage is suddenly decreased by 2.5 % (0.985 pu of nominal voltage). The SVC reacts by generating reactive power (Q=+250 Mvar) in order to keep voltage at 0.979 pu. The 95% settling time is approximately 47 ms. At this point, the DC voltage has increased respectively. Then, at t=0.3 s, the source voltage is increased from 0.95pu to 1.05 pu of its nominal value. The SVC reacts by changing its operating point from capacitive to inductive in order to keep the voltage at 1.02 pu. At this point, the SSSC absorbs 250 Mvar and the DC voltage has been lowered. From the initial trends, it has been observed on the SSSC primary voltage and current that the current is changing from capacitive to inductive in approximately one cycle. Finally, at t=0.5 s the source voltage in set back to its nominal value and the SSSC operating point comes back to zero otherwise SSSC continuous inject voltage and DC voltage will be remained 15kV.
2. The second waveform indicates the phase Iabc current during the above mentioned SSSC operations. Three phases current was +/- 5pu for 0.3 seconds. As the voltage injection started, all three phases current improved from +/- 5 to +/- 10pu as required.
3. The third waveform indicates the magnitude of voltage injected against the reference voltage. Magenta trace shows the reference value (0.09pu) and yellow trace shows the measured value, it varied from 0.1pu to 0.09pu within 0.012 second.
4. The fourth waveform indicates the measured DC voltage (15KV/Maximum) during the inductive or capacitive mode of SSSC operations.
5. The fifth waveform indicates the Real power (400MW) being exchanged in between United Arab Emirates and Oman during SSSC operations.
6. The sixth waveform indicates the required reactive power being injected in between United Arab Emirates and Oman during SSSC operations.

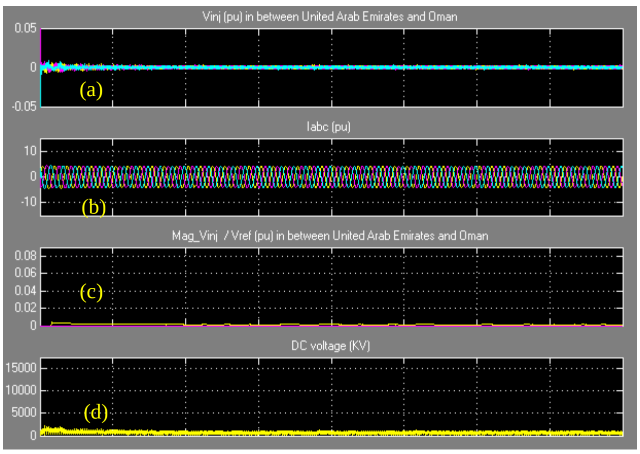

FIG.3 NETWORK OPERATIONAL TRENDS WITHOUT SSSC (A) VOLTAGE INJECTION (B) IABC CURRENT (C) INJECTION VOLTAGE MAGNITUDE AND REFERENCE VOLTAGE (D) DC VOLTAGE

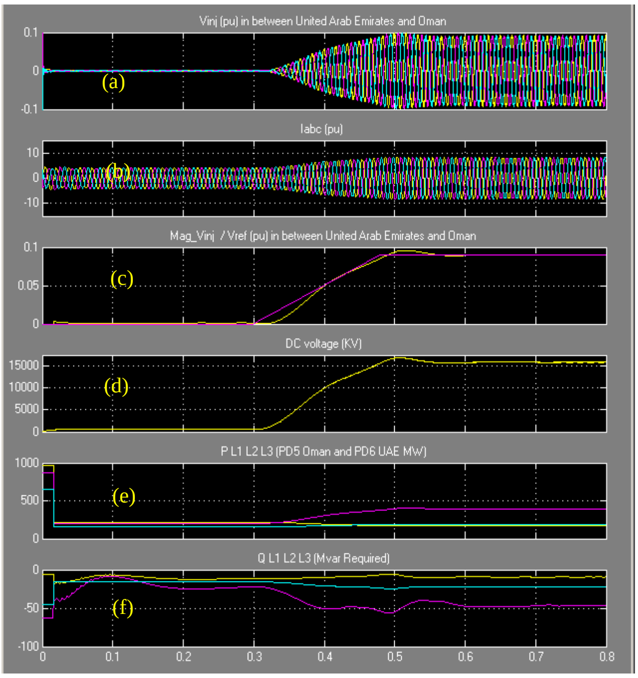

FIG.4 INDICATES THE NETWORK OPERATIONAL TRENDS WITH SSSC

(a) voltage injection (b) Iabc current improvement (c) injection voltage magnitude and reference voltage (d) DC voltage produced (e) power exchange in between Oman and UAE (f) reactive compensation in between Oman and UAE

Novel Control of SSSC Device Operations

FIG.1. indicates the control schematic of SSSC device. This schematic comprises of measured and reference values control blocks of the SSSC device operations. The first control block.1 will collect the measured voltage data from the Al-Fuaha (UAE) and Wasset Substation (Oman) as mentioned in the schematic. The second control block.2 will collect the measured current data from the same substations. The third (block.3) and fourth (block.4) will indicates the defined reference values of current and voltage of the target substations. These measured and reference values are plugged in control block.5 to determine the deviation(s) of each defined parameter. These deviations could be +/- (2, 4 &6)% and will be sent to control topology for final action based on the deviations, the control loop will respond to inject or absorb reactive power to/from the GCC power grid as demonstrated FIG.7,9 and 11 . These values are adjusted based on corresponding PI control values as demonstrated in Table 8 and FIG.5. Each control boundary tuned by introducing new PI control parameters in order to adjust minimum, medium and maximum reactive power compensation in between the Oman and UAE [7],[9],[11].

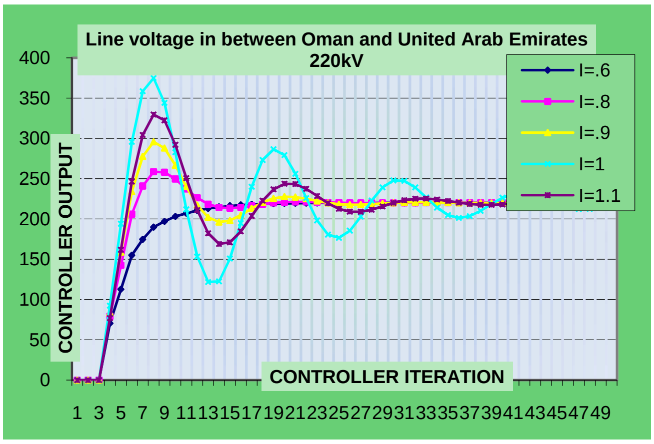

FIG.5. INDICATES THE PI CONTROL VALUES RESPONSE

Based on the research study, the concept is to develop and customize and optimize the SSSC controller operating and control system by incorporating new control compensation technique's parameters. In this method, the control system has three operating and control boundaries in order to run the system successful.

In the first operating scenarios the SSSC controller can be adjusted +/- CL2 (inductive)/CC2 (capacitive) at minimum to eliminate+/- 2% power deviation by incorporating first set of P & I values(P=0.32; I= 0.65 and SP=220kV) as demonstrated in FIG.5, 6, 7 and Table 8.

- FIG.6 first waveform indicates the three phase voltage injection against the reference value with 2% deviation and injected voltage reached at 0.078pu. Second waveform indicates the drop in three phase current due to 2% injection voltage deviation. And the three phases current reached +/-9pu in between the Oman and UAE. Third waveform indicates the injected voltage magnitude against the reference value 0.078pu based on the 2% deviation introduced in the system. Fourth waveforms shows the14.5 kV DC voltage dropped during the defined injected voltage deviation.
- FIG.7. first waveform indicates the injected voltage is equal to reference value after eliminating the deviation in between Oman and UAE. On the same pattern second waveform indicates the improvement in three phase current waveforms after proper voltage injection. Third waveform shows the magnitude of injected voltage is equal to the reference value. Fourth waveform indicates the 15.0kV DC voltage was produced during the compensation factor.

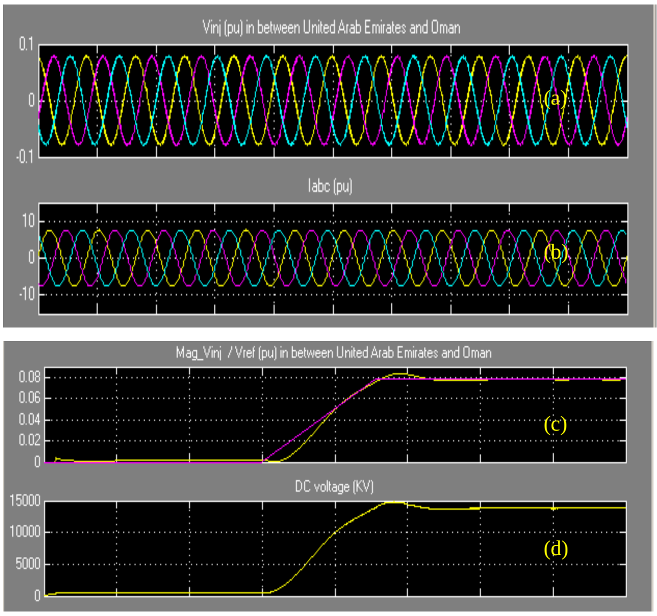

FIG.6. INDICATES THE +/- 2% DEVIATION IN BETWEEN OMAN and UAE

(a) injected voltage deviation 0.078pu (b) due to deviation decline in three phase current waveform (c) voltage magnitude against the reference value (d) 14.5 kV DC voltage produced at 2% deviation

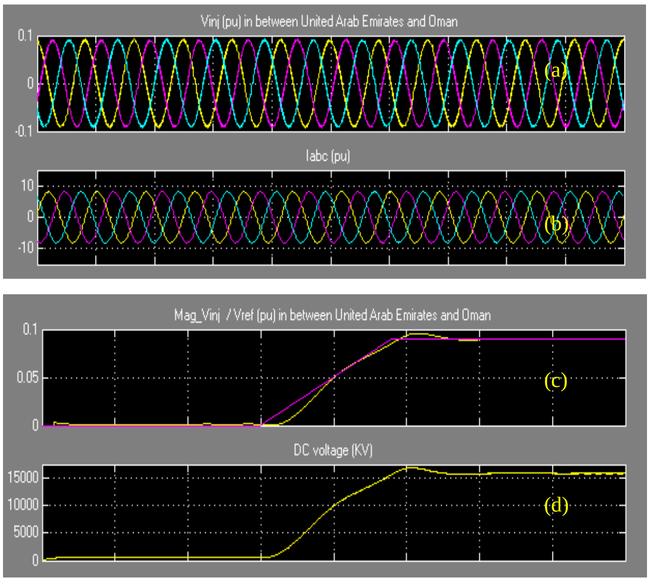

FIG.7. INDICATES THE 2% COMPENSATION AS PER DEVIATION IN BETWEEN OMAN AND UAE

(a) injected voltage deviation 0.080pu (b) improvement in three phase current waveform (c) voltage magnitude against the reference value 0.080pu (d) 15.0 kV DC voltage produced to address the 2% deviation

In the second operating scenarios the SSSC controller can be adjusted +/- CL22 (inductive)/CC22 (capacitive) at medium to eliminate+/- 4% power deviation by incorporating second set of P & I values(P=0.32; I= 0.85 and SP=220kV) as demonstrated in FIG.5, 8, 9 and Table 8[7],[9],[11].

- FIG.8 first waveform indicates the three phase voltage injection against the reference value with 4% deviation and injected voltage reached at 0.076pu. Second waveform indicates the drop in three phase current due to 4% injection voltage deviation. And the three phases current reached +/-8pu in between the Oman and UAE. Third waveform indicates the injected voltage magnitude against the reference value 0.076pu based on the 4% deviation introduced in the system. Fourth waveforms shows the14.0 kV DC voltage dropped during the 4% defined injected voltage deviation.
- FIG.9. first waveform indicates the injected voltage is equal to reference value after eliminating the deviation in between Oman and UAE. On the same pattern second waveform indicates the improvement in three phase current waveforms after proper voltage injection 0.08pu. Third waveform shows the magnitude of injected voltage is equal to the reference value 0.08pu. Fourth waveform indicates the 15.0kV DC voltage was produced during the compensation factor.

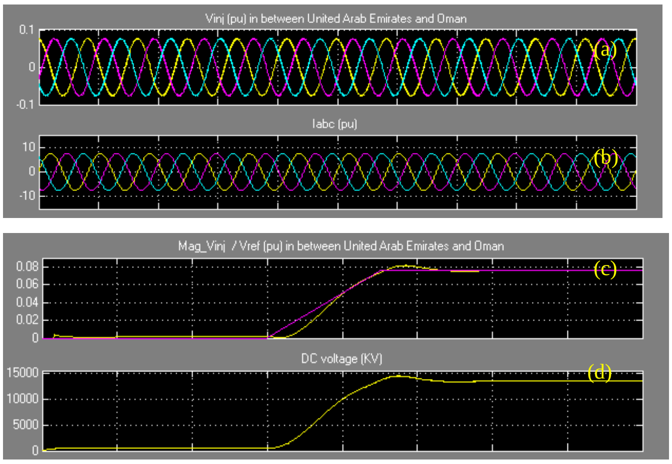

FIG.8. INDICATES +/- 4% DEVIATION IN BETWEEN OMAN/UAE

(a) injected voltage deviation 0.076pu (b) due to deviation decline in three phase current waveform (c) voltage magnitude against the reference value (d) 14.0 kV DC voltage produced at 4% deviation

In the third operating scenarios the SSSC controller can be adjusted +/- CL222 (inductive)/CC222 (capacitive) at maximum to eliminate+/- 6% power deviation by incorporating first set of P & I values(P=0.32; I= 0.95 and SP=220kV) as demonstrated in FIG.7, 10, 11 and Table 8[7],[9],[11].

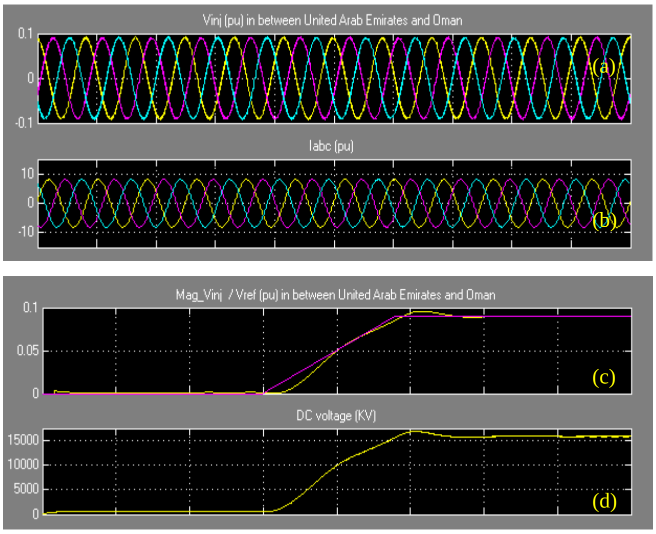

FIG.9. INDICATES THE 4% COMPENSATION AS PER DEVIATION IN BETWEEN OMAN AND UAE

(a) injected voltage deviation 0.080pu (b) improvement in three phase current waveform (c) voltage magnitude against the reference value 0.080pu (d) 15.0 kV DC voltage produced to address the 2% deviation

- FIG.10 first waveform indicates the three phase voltage injection against the reference value with 6% deviation and injected voltage reached at 0.074pu. Second waveform indicates the drop in three phase current due to 6% injection voltage deviation. And the three phases current reached +/-7pu in between the Oman and UAE. Third waveform indicates the injected voltage magnitude against the reference value 0.074pu based on the 6% deviation introduced in the system. Fourth waveforms shows the13.5 kV DC voltage dropped during the 6% defined injected voltage deviation. FIG.11. first waveform indicates the injected voltage is equal to reference value after eliminating the deviation in between Oman and UAE. On the same pattern second waveform indicates the improvement in three phase current waveforms after proper voltage injection 0.08pu. Third waveform shows the magnitude of injected voltage is equal to the reference value 0.08pu. Fourth waveform indicates the 15.0kV DC voltage was produced during the compensation factor.

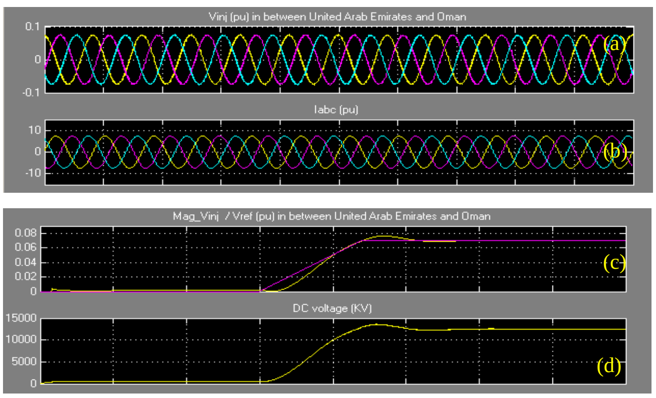

FIG.10 INDICATES +/- 6% DEVIATION IN BETWEENOMAN/UAE

(a) injected voltage deviation 0.074pu (b) due to deviation decline in three phase current waveform (c) voltage magnitude against the reference value (d) 13.5 kV DC voltage produced at 4% deviation

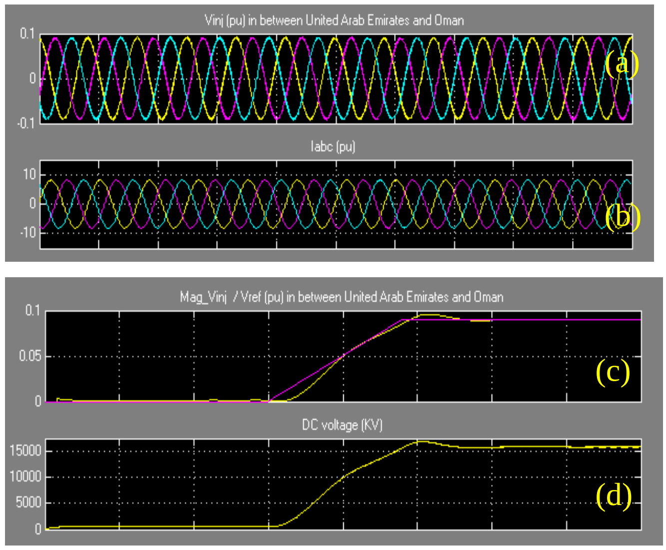

FIG.11 INDICATES THE 6% COMPENSATION AS PER DEVIATION IN BETWEEN OMAN AND UAE

(a) injected voltage deviation 0.080pu (b) improvement in three phase current waveform (c) voltage magnitude against the reference value 0.080pu (d) 15.0 kV DC voltage produced to address the 2% deviation

Observations

FIG.4. illustrates the analysis of SSSC key parameters at United Arab Emirates Al-Fuhah Substation and Al-Wasset Substation (Oman). In the first trace, the waveforms show injected voltage +/-0.05pu which improve the SSSC operations significantly. Second trace indicates phase current operations which oscillate +/- 10pu at s=0.35 second.

Third trace shows the magnitude of voltage injected against the reference voltage after 0.34 second. Fourth trace shows the DC voltage increased from zero to 15kV after 0.3 second and remained at same value for rest of SSSC operations. Fiftieth and sixth traces indicate change in reactive and real power within given time span. In order to enforce a corrective action to minimize the error, all observations are addressed by adjusting the control parameters precisely by considering adequate safety and security margins.

Discussion

Herein, the SSSC device model demonstrates the

impact on the GCC power grid in order to exchange power in between Oman and United Arab Emirates from and to the main transmission system, which is starting from Kuwait to the United Arab Emirates power. The main transmission line is interconnected to KSA, Bahrain, Qatar, Kuwait, United Arab Emirates and Oman to meet industrial and domestic load requirements at different atmospheric conditions. In addition to that, the SSSC model and new control and optimization technique are described in detail and their prompt application in between Oman and United Arab Emirates. The simulated results evidently indicate that SSSC application will deliver promising and sustainable performance in order to improve power system operations in the GCC power grid at large.

Selection Model

FACTS devices selection process is described by using Wideband Delphi process estimation technique in section II. Through this technique very strong consensus developed by inviting high level experts from academic and industry to calculate and determine each FACTS device CRV (credible value) by using Equation (1). Based on model's various estimated parameters very promising results are achieved as demonstrated in Table 4 & 5. Such selection process technique may be used in future as applicable [17],[18].

Controller Significance

SSSC model controller has developed three control limits (minimum (+/- CL2/CC2), medium (+/- CL22/CC22), and maximum (+/- CL222/CC222) compensation. This controller oscillates in between +/- 6% at both sides of transmission lines to adjust reactive power compensation as required. These control boundaries will communicate and adjust based on sending and receiving end voltage deviation. The controller will oscillate and inject or absorb controlled reactive power based on corresponding PI controller values of each operating boundary as demonstrated in Table 8 and FIG.5. These control boundaries will effectively operate when more than one FACTS device will be in operations at different location on the GCC power grid. These will communicate to each other based on voltage deviation at sending and receiving ends [17], [18].

SSSC Impact on the GCC Power Grid

The SSSC model demonstrates very strong impact in between Oman and UAE in the GCC power grid in order to achieve following benefits. Fig 3 and 4 indicate the voltage profile at receiving end before and after the SSSC (switched off and on)

- 400 MW power exchanged at Al-wasset Substation Oman
- 900MW power exchanged at Al-Ouhah substation UAE.
- Improved load flow and power system stability
- Meeting industrial and domestic load requirements at different atmospheric conditions without any constraint.

The simulated results clearly show that SSSC application will deliver promising and sustainable performance in order to improve power system operations through implementing emerging technologies, as and when appropriate[17],[18].

Conclusions

The SSSC application on the GCC power grid transmission line compensation is the subject of considerable interest. This study demonstrates novel control technique of SSSC distributed control system to generate and absorb reactive power at three levels of compensation (minimum, medium and maximum) based on control and operational deviation in between Oman and United Arab Emirates. The results indicate the potential performance to improve the power system network operations and control with high degree of precision in between Oman and United Arab Emirates. Majorly, the GCC power network will entirely increase the power system loadability, reduce the losses and enhance sustainability of the power system performance. The results also show that SSSC is flexible with exceptional dynamic capability to enahnce the power system stability margin on the GCC power grid. Based on these results, SSSC is a very strong candidate to be implemented in between the United Arab Emirates and Oman on the GCC power grid. It also exhibits positive impact on neighbouring countries' KSA, Qatar, Kuwait, Bahrain, power system operations.

Appendix

Appendix indicates the SSSC control schematic and its control and configuration parameters.

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Abbreviations and Acronyms

TERMS	:	FUNCTIONS
CC2,CC22,CC222	:	SSSC 1st, 2nd and 3rd capacitive control pattern developed in Matlab
CL2,CL22,CL222	:	SSSC 1st, 2nd and 3rd inductive control pattern developed in Matlab
GCC	:	Gulf cooperative Council (Qatar, Oman, Bahrain, Kuwait and Saudi Arabia)
V_ reference	:	Reference voltage as defined in control block
Va	:	Primary voltage on the GCC power grid
Ia	:	Primary current on the GCC power grid
Alpha	:	Firing angle to control the reactive power
Vac	:	AC voltage on the GCC power grid
Vdc	:	DC voltage on the STATCOM side
Kp	:	Proportional Gains to control STATCOM device response
Ki	:	Integral Gains to control the STATCOM device response

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APPENDIX NO.1

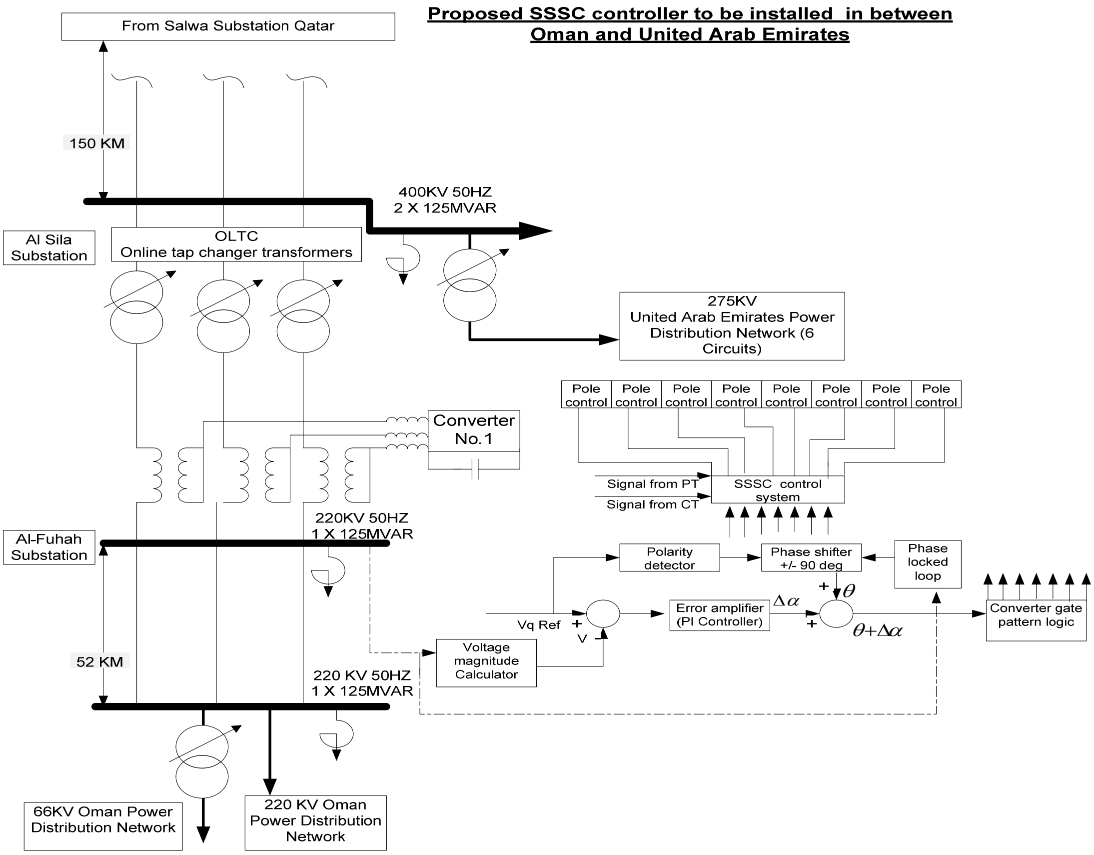

FIG.5. INDICATES SSSC CONTROL SCHEMATIC OMAN AND UNITED EMIRATES

TABLE 6: EXISTING REACTIVE POWER AND DISTANCE

Existing Power System	Reactive Power	Distance
Reactive Power Demand at Al-Ghunan substation KSA	500MVAR	Al Fadhili substation (KSA) to Al-Ghunan Substation (KSA) =114 Km
Reactive Power Demand at Al Jasra substation Bahrain	850MVAR	Al-Ghunan Substation (KSA) to Slawa Substation (Qatar) = 288Km
Reactive Power demand at Al-Salwa Substation	500MVAR	Slawa Substation (Qatar) to Doha South Substation = 97Km
Reactive Power demand at Doha South Substation	250MVAR	

TABLE 7: MULTIVARIABLE CONTROLLER'S CONFIGURATION OF THE SSSC

SSSC LOCATION: Series connected at Al-wasset substation in between Oman and United Arab Emirates	Iq regular: Kp 12dB; Ki: 35dB	CC2 and LC2 = minimum compensation capacitive or inductive (VC voltage change from 1 to 2%)
Rated SSSC: +/- 250 MVAR	Ref V: 1.0 pu (220kV)	CC22 and LC22 = medium compensation capacitive or inductive (VC voltage change from 2% to 4%)
P (proportional): 0.32 , 0.42 and 0.52 I (integral) 0.6, 0.8, 0.9, 1.1 D (derivative): none	Droop: 0.033pu/100MVA; Kp:14dB; Ki: 3500dB	CC222 and LC222 = full compensation capacitive or inductive (VC voltage change from 4-6%)

TABLE 8 SSSC DEVICE CONTROL PARAMETERS

S.No	DEVICE ID	DEVICE NAME	COUNTRYID STATIONID	CAPACTIVIE CONTROL ID	P (POR)	I (INT)	REFERENCE VOLTAGE(KV)	MEASURED VOLTAGE (KV)	ERROR IN %
1	SS	SSSC	S7/C7	CC2	0.32	0.65	220	214	-2%
2	SS	SSSC	S7/C7	CC22	0.36	0.85	220	211	-4%
3	SS	SSSC	S7/C7	CC222	0.40	0.95	220	207	-6%
4	SS	SSSC	S7/C7	CL2	0.32	0.65	220	224	2%
5	SS	SSSC	S7/C7	CL22	0.36	0.85	220	229	4%
6	SS	SSSC	S7/C7	CL222	0.40	0.95	220	233	6%